THE INFLUENCE OF ROUGHNESS GEOMETRY AND SHIELDS PARAMETER ON FLOW RESISTANCE IN GRAVEL-BED CHANNELS

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ABSTRACT

The spatial variability of bed particles of a gravel-bed channel is analysed and treated experimentally in order to simulate the effects of the arrangement of coarse bed elements on the flow resistance law. For the studied bed patterns, characterized by the concentration Γ of coarser elements arranged on the bed layer, a particle arrangement parameter α is proposed. The α parameter is useful for estimating the intercept b_0 of the semi-logarithmic flow resistance law deduced by flume measurements carried out for the hydraulic condition of large-scale and transition roughness. The differences between the experimental friction factor parameter values and the ones calculated by the proposed semi-logarithmic relationship are explained by the ratio between the Shields parameter and its critical value. The analysis shows that estimates of the friction factor parameter are not improved by introducing the Froude number into the flow resistance law. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Cobble and boulder bed channels may be defined by a median bed material size exceeding about 64 mm, large-scale or intermediate roughness (i.e. a depth to sediment height ratio <15) and no vegetal effects. They are also characterized by steep slopes and large width to depth ratios (Bathurst, 1982).

This paper seeks to refine the flow resistance relationships for such channels. It builds on previous experimental studies (Ferro and Giordano, 1991, 1993) which showed that an accurate knowledge of the bed particles (size, concentration of the coarser elements, orientation, spacing, etc.) is necessary in order to evaluate the friction factor parameter $C/\sqrt{g}$, in which C is the Chezy coefficient and g is acceleration due to gravity.

The available flow resistance equations generally characterize the size distribution of the bed particles, obtained by Wolman's sampling method (Kellerhals and Bray, 1971), by using a measure of the particle diameter d_{xx} (d_{50}, d_{84}, d_{90}) for which *xx* per cent (50 per cent, 84 per cent, 90 per cent) of the particles are finer. This characteristic size is assumed to be different for the two hydraulic conditions of small-scale roughness and large-scale roughness (Bathurst *et al*., 1981; Bray, 1987).

Experimental investigations carried out for the large-scale roughness condition (Bathurst, 1978; Hey, 1979; Bathurst *et al*., 1981) have shown that besides the characteristic diameter d_{xx}, representing the size of the bed particles, the concentration Γ of coarser elements has to be introduced into the flow resistance law (O'Laughlin and MacDonald, 1964; Pyle and Novak, 1981). Γ is a parameter that provides a measure of the frequency of the coarser elements in the bed layer.

In fact, if we consider a bed reference area with a bed layer of a given size distribution, the relationship between the flow resistance and the number N of coarser elements is not monotonic. Initially, when N increases, both the drag resistance and the resistance due to the arrangement of the elements increase. When the N value is so high that the coarser elements approach each other, the wakes generated by each coarser element do not extinguish before meeting the next element (*wake-interference flow*) (Morris, 1959) and the flow resistance begins to decrease again.

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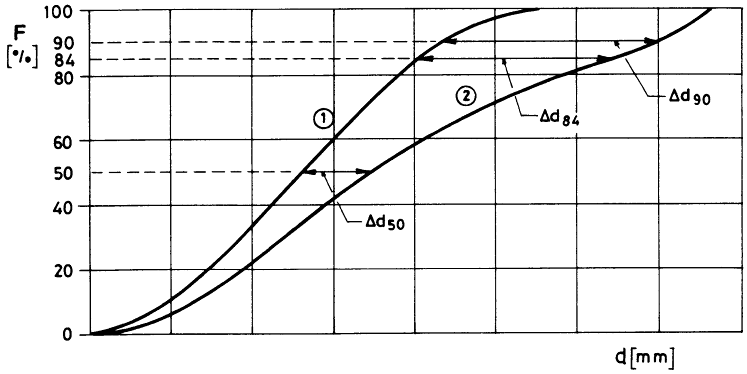


Figure 1. Grain distributions of bed arrangement with different numbers of coarser elements

In a previous study, Ferro and Giordano (1991) carried out flume measurements in order to study the flow resistance law for h/d_{50} values ranging from 1 to 6 (large-scale roughness condition), in which h is the uniform flow depth measured by using a reference level obtained by replacing the *actual* bed layer with an *equivalent* one having the same volume and constant thickness. The authors showed that the influence of concentration of coarser elements on the flow resistance law could be represented by using d_{84} and d_{90} as characteristic sizes. For example, if the bed layer has the size distribution labelled as type 1 in Figure 1 and some coarser elements are added, the bed particle size distribution becomes type 2: the change in the particle diameter is wider for increasing values of the frequency F. In other words, for large-scale roughness, the variation in the concentration Γ can be represented by the variation in d_{84} or d_{90}.

Hey (1979) and Bray (1980), in order to take into account the characteristic granulometric sorting of a gravel-bed river in which coarser bed particles are arranged (coarser gravel and cobbles), suggested the use of an equivalent sand grain roughness k_s (Keulegan, 1938) equal to $3{\cdot}5d_{84}$. For a given hydraulic radius and d_{84}, the multiplier 3·5 allows us to obtain smaller values of the friction coefficient $C/\sqrt{g}$, representing additional energy losses due to jet and wake processes (Morris, 1959; Marone, 1970) occurring around larger grains.

For a gravel-bed river, $3{\cdot}5d_{84}$ is approximately equal to d_{99} (Burkham and Dawdy, 1976; Hey, 1979) so that the roughness height will be practically coincident with the maximum diameter d_{max} of the bed particles. These findings can be explained by taking into account the armouring process within a non-uniform gravel bed (Gessler, 1971; Little and Mayer, 1976; Parker and Klingeman, 1982; Parker *et al*., 1982; Shen and Lu, 1983; Sutherland, 1987). In fact, in evaluating the friction factor, according to Gessler's (1990) results and an experimental investigation of Ferro *et al*. (1993) on some Calabrian rivers, a *control roughness*, which can be greater than the maximum particle size d_{max} of the bed grain mixture, has to be considered.

In order to characterize a gravel bed both with a *scale parameter* of the grain size distribution (d_{xx}) and with a *pattern parameter* varying with Γ, Colosimo *et al*. (1983, 1986, 1988) suggested the following flow resistance law:

$$\frac{C}{\sqrt{g}} = a\log\frac{bh_{\mathrm{m}}}{Md_{84}} \tag{1}$$

in which a is a numeric constant, b is a coefficient representing the shape of the river cross-section, h_{m} is the mean water depth and M is the uniformity modulus of the cumulative frequency distribution of the bed particles as defined in Figure 2.

However, in order to fully characterize a gravel bed, we need information on the arrangement, the shape as well as the size of the coarser bed particles. The arrangement can be represented by the longitudinal distance L_{f} between the coarser bed elements, i.e. the distance measured in the flow direction, and by the transverse distance L_{t} between the coarser bed elements measured in the cross-sectional plane. The knowledge of L_{f} allows

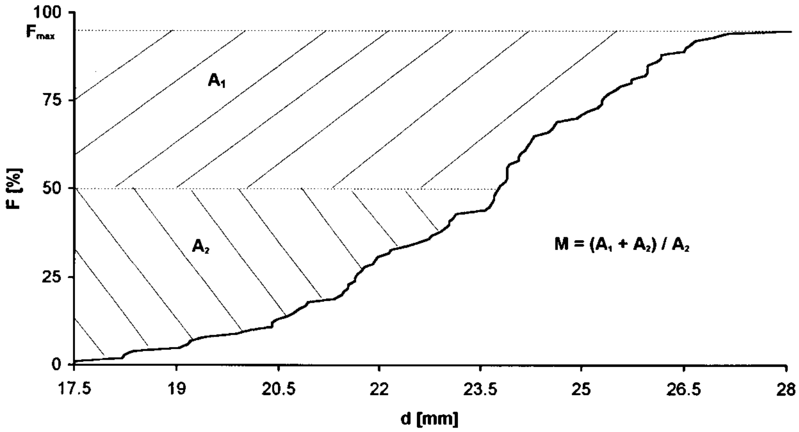


Figure 2. Estimation criteria of the uniformity modulus

one to establish if there is any interference among the eddies with horizontal axis generated by the elements (Morris, 1959) in the downstream direction. The transversal distance L_t indicates potential interference among the eddies with a vertical axis generated by the roughness elements. The shape of the bed element is indirectly taken into account in the choice of a roughness height.

By using this detailed characterization of roughness geometry and applying the Riabucinski–Buckingham theorem for a straight channel with no vegetation, the following functional relationship is obtained (Colosimo *et al*., 1988):

$$\frac{C}{\sqrt{g}} = f\left(Re, Fr, \frac{R}{d_{xx}}, \frac{L_f}{d_{xx}}, \frac{L_t}{d_{xx}}, \Gamma, \tau^\star\right) \tag{2}$$

in which *Re* is the flow Reynolds number, *Fr* is the flow Froude number and τ^* is the Shields (1936) parameter.

This paper aims to expand on this relationship and evaluate the effects of the coarser bed element arrangement on the flow resistance law. First, the spatial variability of the bed particles is studied and a particle arrangement parameter, representing the concentration and the arrangement of coarser elements, is proposed. This index is then used to analyse the results of an experimental flow resistance study carried out in a gravel-bed flume. The runs are carried out for different arrangements of coarser particles randomly disposed on the bed layer, which is one grain thick (Figure 3). The runs are characterized by a different number *N* of coarser elements in the reference area ($0{\cdot}6\,\text{m}\times0{\cdot}6\,\text{m}$), and for the hydraulic conditions ($1{\cdot}7\leq h/d_{84}<9{\cdot}0$) of a large-scale and transition roughness according to Bathurst *et al.* (1981). Other investigations show the influence of the Shields parameter and Froude number on the resulting flow resistance.

EXPERIMENTAL INSTALLATION AND MEASUREMENTS

The experiments were carried out using the laboratory flume of the Hydraulics Institute at the University of Palermo (Figure 4). The flume is 14·0 m long, 0·6 m wide and 0·6 m deep, and is divided into two parts. The first part (4 m long) has steel sides. The second part (10 m long) has glass sides. In the end section of the channel, a sluice gate is installed to change the water depth without changing the experimental discharge, in order to obtain flows with different Froude numbers but constant discharge. In this study, all experimental runs were carried out with the sluice gate open.

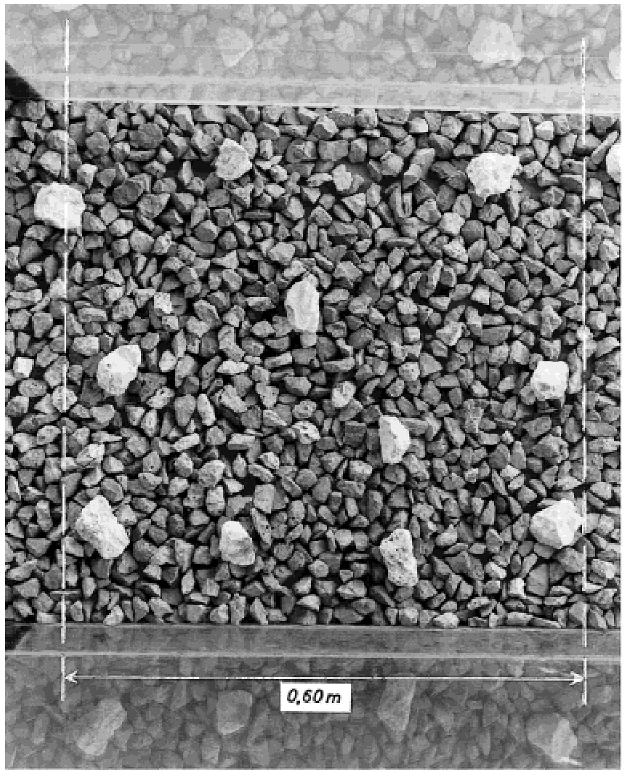


Figure 3. Example of experimental bed arrangement (II)

The water discharge was measured by a concentric orifice plate installed in the feed pipe. The measuring reach (3·6 m long), bounded by two wooden beams, was located 3·7 m from the entrance section in order to avoid large-scale disturbance. In the measuring reach, three piezometers were installed. The water depth was calculated as the mean value of three measurements. The water temperature, useful for side-wall correction by Johnson's (1942) method, was measured with a standard thermometer.

As described by Ferro and Giordano (1991), the reference level (Hinze, 1975; Schlichting, 1960; Zippe and Graf, 1983) was obtained by replacing the *actual* bed layer with an *equivalent* one having the same volume and constant thickness. The equivalent thickness was calculated for the bed layer ($N=0$) only and was considered constant for the experiments carried out with different concentrations of coarser elements. In each run the flume was divided into reference areas 0·6 m×0·6 m and in each area a fixed number N of coarser elements was randomly arranged (e.g. Figure 3), i.e. the N coarser elements were not localized on a row or on a column.

In Table I, the number N of coarser elements randomly arranged in each reference area, the concentration $\Gamma=100(N/N_{max})$, in which N_{max} is the maximum number of coarser elements which it is possible to arrange in the reference area (170), and the characteristic sizes d_{50}, d_{84}, d_{90} and d_{max} of the four investigated bed arrangements are listed.

The bed particle grain-size distributions were obtained by Wolman's sampling method. The size ranges of the bed layer particles and of the coarser ones are 17·7–30 mm and 41–56·1 mm, respectively. The median diameter of the bed layer $d_{50,BL}$ is equal to 23·8 mm and the median diameter of the coarser particles D_{50} is 46 mm.

The gravel bed of each run is essentially a sediment mixture of two components: the *ground* component or bed layer ($N=0$) and the *coarser* component. The mixture can be characterized by the two median diameter ($d_{50,BL}$ and D_{50}) of each component and by the concentration Γ which represents the weight of the coarser component in the mixture.

The basic experimental data are listed in Table II for each of the bed arrangements investigated.

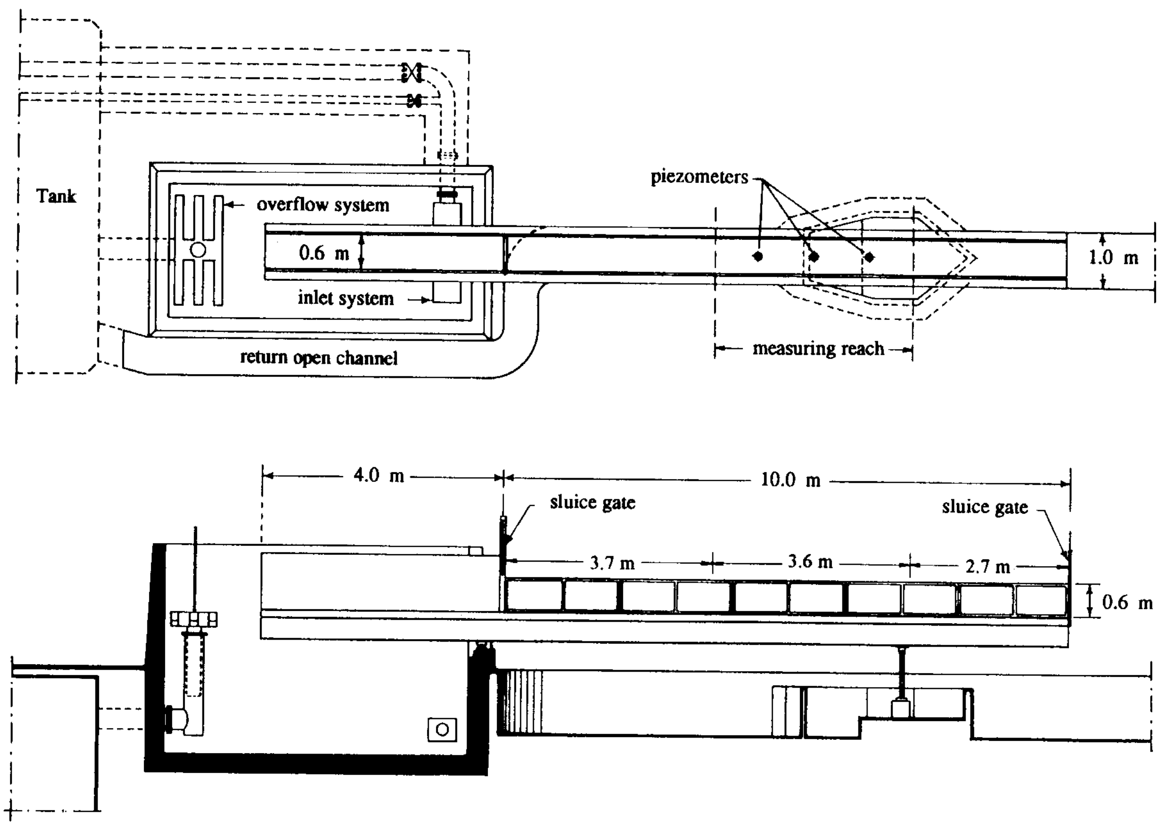


Figure 4. Experimental lay-out

Table I. Characteristic data of the experimental bed arrangements

Bed arrangement	N	Γ (%)	d_{50} (mm)	d_{84} (mm)	d_{90} (mm)	d_{max} (mm)
I	0	0	23·8	26·0	26·5	30·0
II	10	5·9	24·9	27·4	29·9	56·1
III	20	11·8	25·0	28·1	44·0	51·4
IV	40	23·5	24·1	42·1	45·0	52·9
I−*n*	0	0	27·9	33·0	34·7	42·3
II−*n*	10	8·3	27·5	34·1	37·1	57·2
III−*n*	20	16·7	28·5	35·7	41·7	58·2

Table II. Basic experimental data

Bed arrangement	Number of runs	Q ($l\,s^{-1}$)	h (cm)	i (%)	$Re \times 10^4$	τ^*/τ^*_{cr}	Fr
I	45	10–162	6·0–22·9	0·25–2·5	6·1–67	0·06–0·75	0·36–0·96
II	44	18–140	7·2–21·5	0·25–1·2	11·0–64	0·10–0·76	0·40–0·88
III	42	12–129	6·6–21·4	0·25–1·5	7·1–58	0·05–0·85	0·29–0·83
IV	39	13–137	7·2–22·3	0·25–1·5	7·9–59	0·10–0·87	0·30–0·79
I−*n*	37	34–115	7·9–17·1	0·50–1·5	17·3–49	0·17–0·79	0·63–1·05
II−*n*	42	11–110	5·0–17·6	0·50–1·5	5·9–47	0·12–0·92	0·40–0·87
III−*n*	43	12–115	6·2–18·3	0·50–1·7	6·4–50	0·13–0·98	0·34–0·88

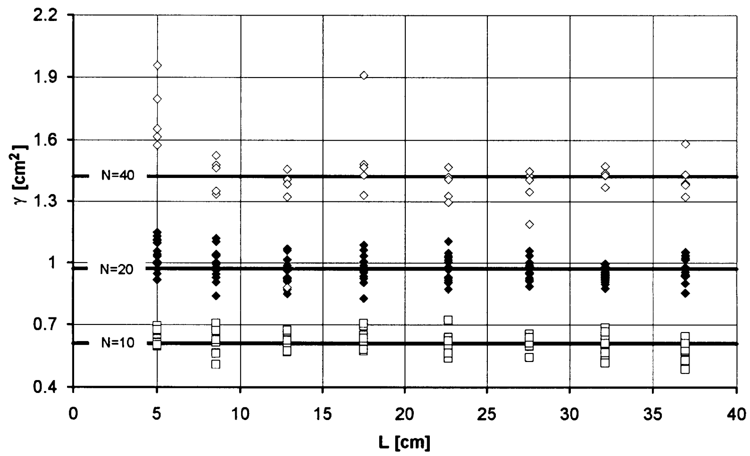


Figure 5. Relation between γ and L for coarser elements randomly arranged and for different Γ values

Table III. Characteristic parameters of the experimental bed arrangements

Bed arrangement	N	Γ (%)	γ_N (cm^2)	α	M
I	0	0	0·070	1·00	2·21
II	10	5·9	0·609	8·70	2·34
III	20	11·8	0·973	13·9	2·43
IV	40	23·5	1·422	20·3	2·55
I$-n$	0	0	0·262	1	2·61
II$-n$	10	8·3	0·635	2·43	2·87
III$-n$	20	16·7	1·196	4·57	2·78

RESULTS

Spatial arrangement of the bed particles

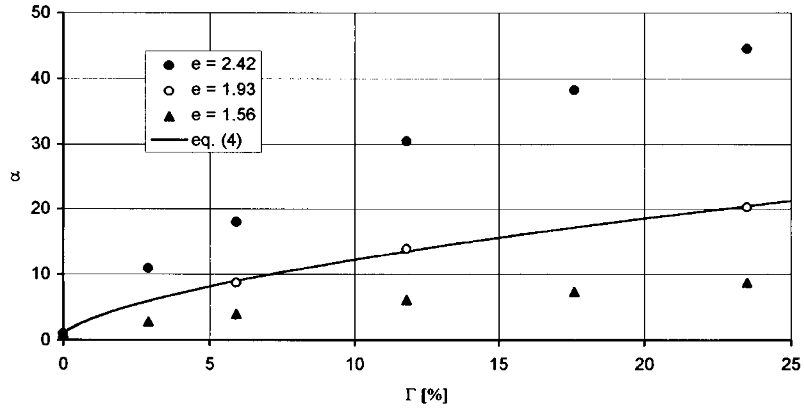
The high irregularity of gravel-bed surfaces, due to the arrangement of the particles, suggests that the theory of fractals (Mandelbrot, 1982) or the variogram analysis (Oliver and Webster, 1986; Clifford *et al*., 1992) may be useful in studying their geometric properties. The two approaches are equivalent when, for the studied processes, a spatial dependence exists at all scales. In this paper the spatial variability of the diameter of 100 bed elements (N coarser particles and 100–N elements of the bed layer), localized in each experimental reference area, is described using the variogram function.

The analysis showed that, for given N, the variance γ of the particle diameter is constant and is independent of the distance vector L (Figure 5); the pure nugget variogram shows that a spatial correlation pattern for the particle diameter does not exist. In other words, for a random arrangement the variogram function is not affected by the position of the N coarser particles, i.e. all bed arrangements of given concentration Γ are characterized by the same γ value.

Table III, for each bed arrangement, lists the number N of coarser particles, the concentration Γ expressed as a percentage, the variance γ_N (cm^2) of the particle diameter corresponding to a random bed arrangement of N coarser particles and the ratio:

$$\alpha = \frac{\gamma_N}{\gamma_0} \tag{3}$$

in which γ_0 is the variance of the particle diameter corresponding to the non-uniform bed layer ($N=0$, i.e. bed arrangement type I listed in Table I).



Relationship between α and Γ for different $D_{50}/d_{50,\,BL}$ values

Table IV. Values of K for the considered mixture

e	K
2·42	22·00
1·93	6·14
1·56	1·50

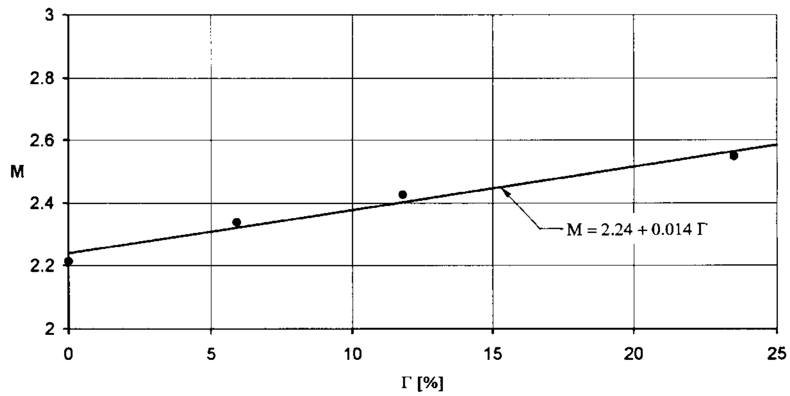


Figure 7. Relationship between M and Γ

In order to establish how the particle arrangement parameter α depends on both the concentration Γ and the grain-size distributions of the bed layer ($N=0$) and of the coarser particles, the spatial variability of the bed particle diameter was studied by using bed arrangements characterized by different values of Γ and of the ratio $e=D_{50}/d_{50,BL}$. In particular, this spatial variability was studied for the mixtures used in the flow resistance experimental runs, characterized by $e=1{\cdot}93$, and for the other two series of mixtures characterized by the same Γ values and e values (2·42 and 1·56).

Figure 6 shows that the relationship between α and Γ is expressed by the following equation:

$$\alpha=[K(e)\Gamma+1]^{0{\cdot}606} \tag{4}$$

in which coefficient K depends on the ratio e (Table IV). Equation 4 shows that the α parameter synthesizes two effects (boulder concentration and size ratio between the two mixture components) which affect the flow resistance in a gravel-bed channel.

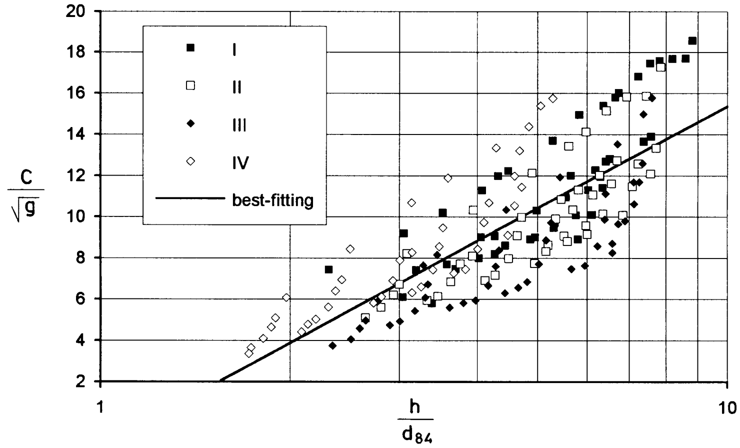


Figure 8. Semi-logarithmic relationship between $C/\sqrt{g}$ and h/d_{84}

As suggested by Colosimo *et al*. (1988), the uniformity modulus M corresponding to the four bed arrangements used in the flow resistance runs (Table III) was also calculated. Figure 7 shows that for the investigated bed arrangements, M depends strongly on concentration Γ.

Flow resistance law

In order to take into account the effects of the coarser bed element arrangement on the flow resistance law, the investigations described above suggest that the bed arrangement needs to be characterized by a *scale* parameter (D_{50}, $d_{50,BL}$, d_{50}, d_{84} d_{90}), a particle *size distribution* parameter (M, Γ) and a particle *arrangement* parameter α.

First, following the results of previous researches (Ferro and Giordano, 1990, 1991) carried out for a hydraulic condition of large-scale and transition roughness ($0{\cdot}9 \leq h/d_{84} < 4$), the semi-logarithmic relationship given in Equation 5 was fitted to 170 experimental pairs (h/d_{84}, $C/\sqrt{g}$) obtained by the flume measurements corresponding to a wider range of the depth/sediment ratio ($1{\cdot}7 \leq h/d_{84} < 9{\cdot}0$):

$$\frac{\bar{C}}{\sqrt{g}} = -1 \cdot 074 + 16 \cdot 444 \log \frac{h}{d_{84}} \tag{5}$$

This is shown in Figure 8 and has a correlation coefficient r equal to 0·80 and a mean square error (MSE) equal to 4·28. The result of the fit does not improve by using d_{90} ($r = 0{\cdot}80$, MSE = 4·62) and the scatter suggests that another parameter representative of Γ variations should be introduced into the flow resistance law.

By using the M parameter to modify the depth/sediment ratio h/d_{84}, the following relationship was obtained:

$$\frac{\bar{C}}{\sqrt{g}} = -5 \cdot 405 + 15 \cdot 311 \log \frac{h}{M d_{84}} \tag{6}$$

This has an r value equal to 0·85 and MSE = 4·35. This slightly improves the fit and shows that the effect of Γ on flow resistance law cannot be represented by an equivalent roughness equal to Md_{84}.

Consequently, the relationship given in Equation 7 was fitted to the experimental data (h/d_{84}, $C/\sqrt{g}$):

$$\frac{\bar{C}}{\sqrt{g}} = b_0(\Gamma) + b_1 \log \frac{h}{d_{84}} \tag{7}$$

Table V. Coefficients b_0 and α of Equation 8

Bed arrangement	b_0	α
I	−2·00	1·0
II	−3·28	8·7
III	−4·32	13·9
IV	−0·98	20·3
I−*n*	−1·81	1·0
II−*n*	−2·39	2·43
III−*n*	−3·04	4·57

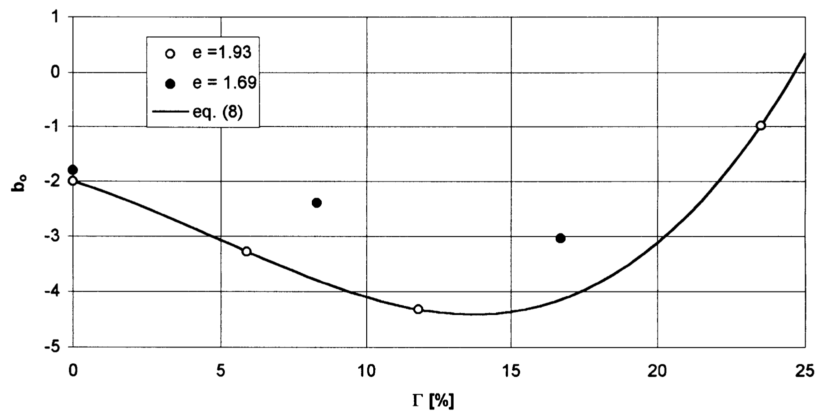


Figure 9. Relationship between coefficient b_0 of Equation 7 and Γ

in which b_1 is equal to 18·9 and b_0 is dependent on the concentration of coarser particles on the bed layer. Equation 7, with b_0 values listed in Table V for the bed arrangements I, II, III and IV, has an r value equal to 0·85 and MSE = 2·89.

The statistical hypothesis that b_1 is independent of Γ was verified by a parallelism test (Hald, 1960) among the four resistance laws, obtained by using the experimental pairs (h/d_{84}, $C/\sqrt{g}$) of each bed arrangement, having the same mathematical form of Equation 7 with b_1 dependent on Γ. This test, based on a statistical parameter which is distributed like a Fisher variable, established that the four separate flow resistance equations are parallel, i.e. b_1 is independent of Γ, with a level of probability equal to 95 per cent.

Figure 9 shows that coefficient b_0 of Equation 7 depends on Γ according to the following relationship:

$$b_0 = -2 - 0{\cdot}1698\Gamma - 0{\cdot}01372\Gamma^2 + 0{\cdot}00097\Gamma^3 \tag{8}$$

which is characterized by the minimum b_0 value for $\Gamma = 14{\cdot}0$ per cent. In other words, for given h/d_{84}, the $C/\sqrt{g}$ values (Equation 7) decrease when Γ increases until $\Gamma = 14{\cdot}0$ per cent then for Γ values greater than 14·0 per cent the $C/\sqrt{g}$ values increase again.

This result can be physically explained by the different energy loss mechanisms which characterize the different experimental bed patterns (I, II, III and IV). For bed arrangements II and III ($N = 10$, 20), the coarser elements are isolated and a semi-smooth turbulent (isolated-roughness) flow regime exists. For bed arrangement IV, N is high and the coarser elements interfere (hyperturbulent or wake-interference flow) (Morris, 1959).

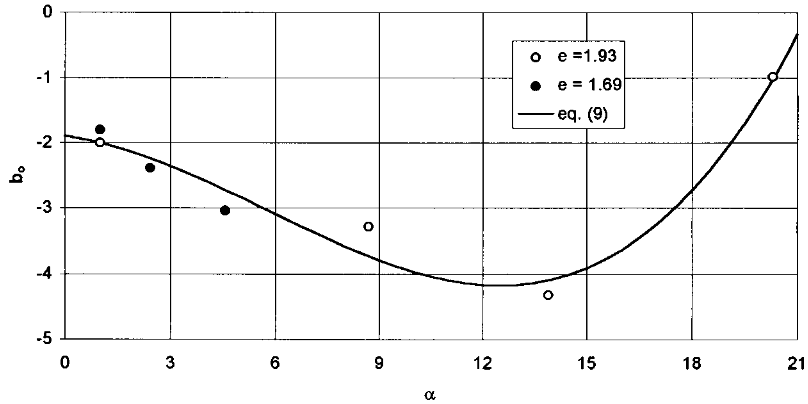


Figure 10. Relationship between b_0 and α for the investigated bed arrangements

To verify whether Equation 8 is dependent on the *e* value (1·93) characteristic of the four experimental bed arrangements (I, II, III, IV), flume measurements were carried out for the three bed arrangements (I-*n*, II-*n*, III-*n*) characterized by $e=1{\cdot}69$. Tables I and III also list characteristic data and parameters of these new bed arrangements. Figure 9 clearly shows that coefficients b_0 of Equation 7 depend on Γ and the ratio $D_{50}/d_{50,\mathrm{BL}}$. In other words, for estimating the intercept of the flow resistance law, the bed arrangement has to be characterized by the size ratio between the two components of the mixture (bed layer and coarse particles) and the boulder concentration.

This last result suggests that b_0 may be estimated using the α parameter, depending on both Γ and *e*, according to the following equation (Figure 10):

$$b_0 = -1{\cdot}8963 - 0{\cdot}07695\alpha - 0{\cdot}03136\alpha^2 + 0{\cdot}00184\alpha^3 \tag{9}$$

which is characterized by $r=0{\cdot}97$ and $\mathrm{MSE}=0{\cdot}134$.

Equation 7, with b_0 values listed in Table V for all investigated bed arrangements (290 experimental data), has an *r* value equal to 0·95 and $\mathrm{MSE}=2{\cdot}58$.

The functional relationship given in Equation 2 shows that if a detailed characterization of roughness geometry is established, then the differences between experimental and calculated $C/\sqrt{g}$ values are due to the Reynolds number *Re*, Shields parameter τ^*, and Froude number *Fr*.

For a gravel-bed channel, the Reynolds number is so high that it does not influence the friction factor (Graf, 1984). Figure 11 compares the experimental pairs (*f*, *Re*), in which *f* is the Darcy–Weisbach friction factor, measured in this study ($7\times10^4 \leq Re \leq 7\times10^5$) with the ranges investigated by other authors (Herbich and Shulits, 1964; Knight and MacDonald, 1979; Bray, 1979; Hey, 1979; Colosimo *et al*., 1988). Figure 11 shows that the experimental pairs are located in the middle of the investigated *Re* ranges, for which the previous authors did not point out a dependence on Reynolds number.

The experimental runs are characterized by flow conditions which differ with respect to the threshold of movement of the bed particles. Since the flume gravel bed is a sediment mixture, the resistance to movement of an individual particle depends on particle size, shape and density, as well as sheltering and exposure to the flow. The entrainment process of the size of individual particles is affected by the overall particle size of the sediment bed, including the particles adjacent to and supporting the individual particle.

In order to take into account the fact that in the experimental runs the coarser elements randomly disposed on the bed layer operate as a stable armour layer, the critical value of the Shields parameter τ^*_{cr} was evaluated using the following relationship (Chin *et al*., 1994):

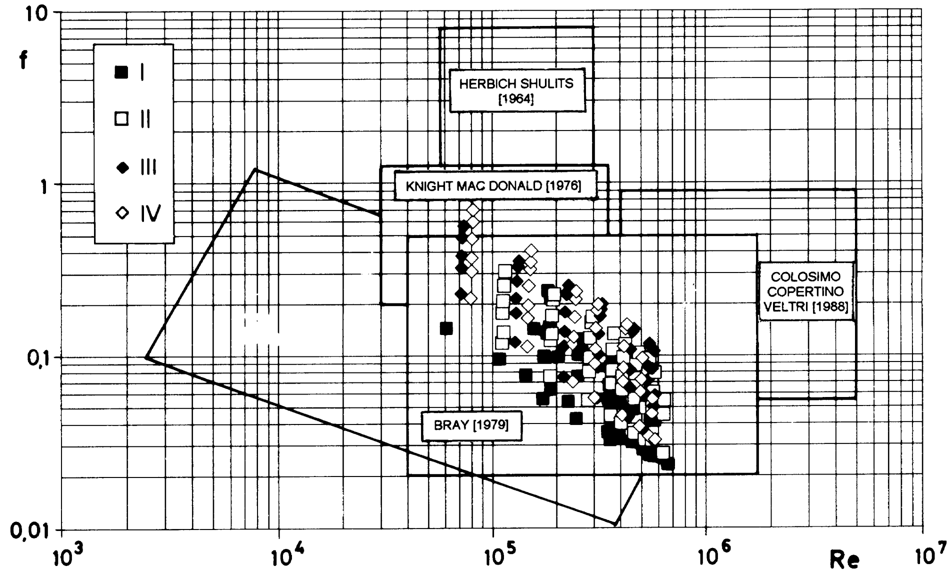


Figure 11. Flow Reynolds number range used in this investigation compared with those studied by other authors

$$\tau^{\star}_{cr} = 0 \cdot 056 \left[\frac{0 \cdot 4}{\left(\frac{d_{max}}{1 \cdot 8 d_{50}} \right)^{0 \cdot 5}} + 0 \cdot 6 \right]^2 \tag{10}$$

in which d_{max} and d_{50} are the maximum and the median size particle of each bed arrangement listed in Table I.

In this way, the threshold of particle movement of the non-uniform sediment bed is seen to depend on the stability of individual large particles and their number on the bed which, in turn, affect the values of the characteristic diameters d_{max} and d_{50} of the mixture.

The Shields parameter (Shields, 1936) was evaluated by the following relationship:

$$\tau^{\star} = \frac{\gamma_w h i}{(\gamma_s - \gamma_w) d_{50}} \tag{11}$$

in which γ_w is the specific water weight, γ_s is the specific weight of the bed particles ($2 \cdot 7\,t\,m^{-3}$) and i is the bed slope.

The τ^*/τ^*_{cr} values vary over a wide range (0·05–0·98) and show that the experimental runs vary considerably with regard to proximity to the condition of incipient motion.

In order to test the influence of the ratio τ^*/τ^*_{cr} on the flow resistance law, the difference δ between the measured $C/\sqrt{g}$ value and the one calculated by Equation 7 was plotted against τ^*/τ^*_{cr}. In Figure 12 the following rough relationship is also plotted:

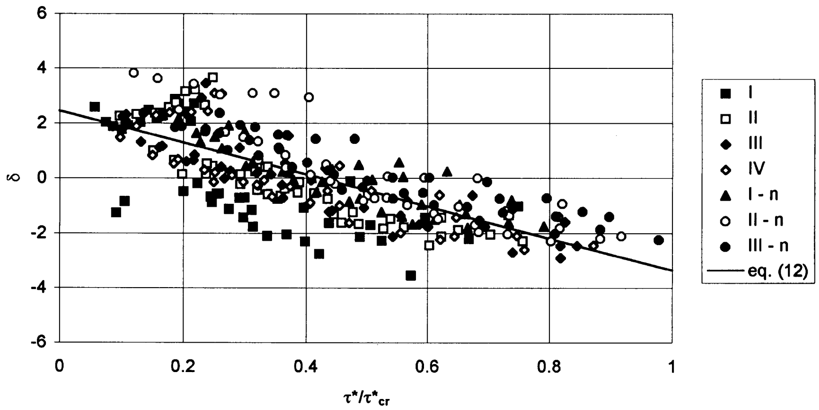


Figure 12. Relationship between δ and τ^*/τ^*_{cr} ratio for the investigated bed arrangements

$$\delta = 2\cdot 45 - 5\cdot 80\frac{\tau^\star}{\tau^\star{}_{cr}} \tag{12}$$

which is characterized by an r value equal to 0·76 and MSE = 1·05. Despite the noticeable scatter of the pairs (τ^*/τ^*_{cr}, δ), introducing Equation 12 into Equation 7 the following flow resistance law is obtained:

$$\frac{C}{\sqrt{g}} = [b_0(\alpha) + 2\cdot 45] + 18\cdot 9\log\frac{h}{d_{84}} - 5\cdot 80\frac{\tau^\star}{\tau^\star{}_{cr}} \tag{13}$$

which is characterized by $r = 0{\cdot}954$ and MSE = 1·10.

By using Equation 13, when the ratio τ^*/τ^*_{cr} increases, i.e. for hydraulic conditions which are always near to the incipient motion condition, the flow resistance also increases ($C/\sqrt{g}$ decreases). This result can be physically explained taking into account that during the experimental runs we observed the rolling of some particles having a diameter less than d_{50}, chosen to calculate the Shields parameter.

The third parameter to be considered is the Froude number and its influence on flow resistance law. The Froude number affects the friction factor when free-surface disturbances take place. In fact, when an element protrudes through the free surface it causes disturbances which represent energy losses (Rouse *et al*., 1963).

According to Bathurst (1982), when *Fr* increases, the relative submergence *R/d* usually increases too, and the number of elements affecting the free surface and the drag of elements decrease; therefore resistance is inversely related to *Fr*. Bathurst *et al*. (1981) developed, by using experimental flume data, a semi-theoretical resistance equation in which Darcy–Weisbach friction factor is inversely related to the Froude number. Although some theories for explaining the influence of Froude number were proposed (Rouse *et al*., 1963; Flammer *et al*., 1970), *Fr* generally does not appear in the resistance equation for gravel-bed channels.

Our measurements showed that the differences between experimental values and those calculated by Equation 13 for $C/\sqrt{g}$, are not significantly correlated with *Fr* ($r = 0{\cdot}03$). From a design point of view, introducing *Fr* into the flow resistance law determines an implicit relationship for calculating the friction factor parameter which has to be solved by an iterative approach. Consequently, this has not been recommended.

CONCLUSIONS

For evaluating the friction factor of a gravel-bed channel, in which some coarser elements are arranged on a bed layer, an accurate knowledge of the bed particle size distribution is necessary. In fact, previous studies suggest that the roughness geometry should be described by both a scale parameter, such as a diameter corresponding to

a given frequency of the bed particle size distribution, and a particle arrangement parameter depending on the concentration of coarser elements randomly arranged on the bed layer. Information about the arrangement and the shape of the coarser elements, which determine other energy dissipative effects, are necessary to complete the granulometric characterization of the bed material.

In order to evaluate the effects of the arrangement of the bed elements on the flow resistance law, therefore, the spatial variability of the bed particle diameter was studied. The analysis showed that if the arrangement of N coarser elements in the experimental area is random, then the variogram function is of the 'pure nugget' type, i.e. all bed arrangements having the same concentration Γ of coarser elements are characterized by the same variance. For each bed arrangement, a particle arrangement parameter α, defined as the ratio between the variance γ_N corresponding to N coarser elements arranged on the bed layer and the variance of the bed layer ($N=0$), was proposed.

In order to test the importance of an adequate bed characterization, a flume investigation with four bed arrangements having different concentrations was carried out. The measurements, carried out for a hydraulic condition of large-scale and transition roughness, showed that the flow resistance law can be expressed by a semi-logarithmic relationship between the friction factor and the depth/sediment ratio.

The flow resistance law has an intercept b_0 which depends on the α parameter; in other words, for estimating the intercept of the flow resistance law the bed arrangement has to be characterized by the size ratio $D_{50}/d_{50,BL}$ between the median diameters of the components of the mixture (coarser particles and bed layer) and the boulder concentration.

The differences between the experimental values of the friction factor $C/\sqrt{g}$ and the calculated ones were explained by the ratio between the Shields parameter τ^* and its critical value τ^*_{cr}. The critical value τ^*_{cr} was estimated by taking into account that the threshold of particle movement depends on the stability of individual large particles and their concentration. The flow resistance law gives decreasing values of $C/\sqrt{g}$ when τ^*/τ^*_{cr} increases. In other words, hydraulic conditions which are near to the incipient motion condition are also characterized by greater energy dissipative phenomena. This result can be physically explained by the fact that, during the experimental runs, rolling of bed particles having a diameter less than the d_{50}, used to calculate the Shields parameter, was observed.

Finally, the analysis showed that the introduction of the Froude number into the flow resistance law does not significantly improve the estimate of the friction factor parameter.

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